26th International Symposium on Spin Physics (SPIN 2025)

山东大学
SHANDONG UNIVERSITY

Global quark spin correlations in relativistic heavy ion collisions

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September. 2025

- Ji-peng Lv, Zi-han Yu, Zuo-tang Liang, Qun Wang, Xin-Nian Wang, Phys. Rev. D 109, 114003 (2024)
- Zhe Zhang, Ji-peng Lv, Zi-han Yu, Zuo-tang Liang, Phys. Rev. D 110, 074019 (2024)
- Ji-peng Lv, Zi-han Yu, Zuo-tang Liang, 【paper in preparation (2025)】

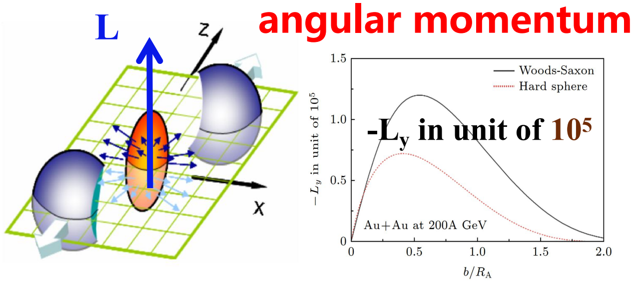
Outline

1. Introduction
2. Description of quark spin correlations in HIC
3. Correlations in HIC using non-relativistic quark combination model
    - Spin density matrix for vector mesons
    - Global hyperon polarization
    - Global hyperon-(anti)hyperon spin correlation
    - Numerical estimates
4. Summary and outlook

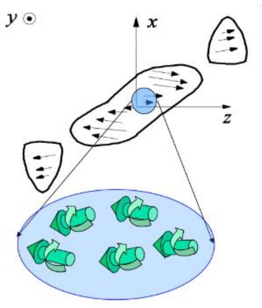
1 Introduction

Zuo-Tang Liang & Xin-Nian Wang, PRL 94, 102301(2005); PLB 629, 20 (2005)

Huge orbital angular momentum



QCD spin-orbital interaction →



Global quark polarization

hadronization →

- **Global hyperon polarization**

$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

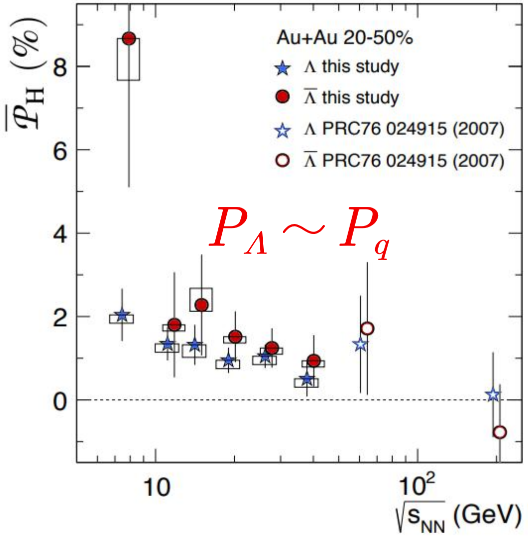
- **Global vector meson spin alignment**

$$\rho_{00}^V = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}}$$

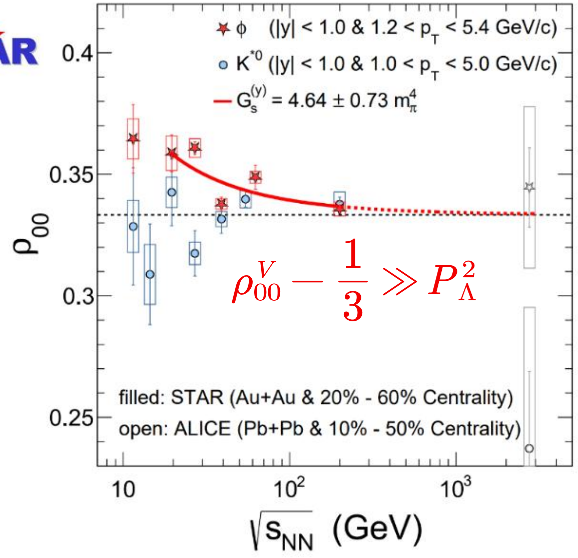
$$\rho_{00}^V - \frac{1}{3} \sim P_q^2$$

STAR, Nature 548, 62-65 (2017).

Cover Article



STAR, Nature 614, 244 (2023).



What dose it tell us ?

How can we understand it ?

1 Introduction

Zuo-Tang Liang & Xin-Nian Wang, **PRL 94, 102301(2005); PLB 629, 20 (2005)**

Quark spin density matrix

$$\hat{\rho}^{(q)} = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

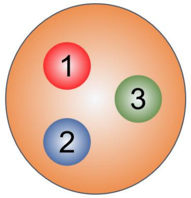
only diagonal elements

Quark combination

Hyperon: $q_1 + q_2 + q_3 \to H$

$$\hat{\rho}^{(q_1 q_2 q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$$

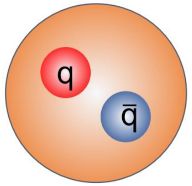
$$\rho^H_{m'm} = \langle j_H, m' | \hat{\rho}^{(q_1 q_2 q_3)} | j_H, m \rangle \qquad P_H = \sum_{i=1}^{3} c_i P_{qi} = P_q$$



Vector meson: $q_1 + \bar{q}_2 \to V$

$$\hat{\rho}^{(q_1 \bar{q}_2)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(\bar{q}_2)}$$

$$\rho^V_{m'm} = \langle j_V, m' | \hat{\rho}^{(q_1 \bar{q}_2)} | j_V, m \rangle \qquad \rho^V_{00} = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} \sim \frac{1 - P_q^2}{3 + P_q^2}$$



It was for the most simplified case:

① P_q was taken as a constant, no fluctuation, **no spin correlations**

② no other degree of freedom (d.o.f.)

1 Introduction

Consider fluctuation and/or other degree of freedom

Hyperon: $q_1 + q_2 + q_3 \to H$

$$P_H = \left\langle \left\langle \sum_{i=1}^{3} c_i P_{qi} \right\rangle_H \right\rangle_S = \sum_{i=1}^{3} c_i \langle P_{qi} \rangle = \langle P_q \rangle$$

Vector meson: $q_1 + \bar{q}_2 \to V$

$$\rho_{00}^V = \frac{1 - \langle P_{q_1} P_{\bar{q}_2} \rangle}{3 + \langle P_{q_1} P_{\bar{q}_2} \rangle} \neq \frac{1 - \langle P_{q_1} \rangle \langle P_{\bar{q}_2} \rangle}{3 + \langle P_{q_1} \rangle \langle P_{\bar{q}_2} \rangle}$$

$$\langle P_q P_{\bar{q}} \rangle = \langle \langle P_q P_{\bar{q}} \rangle_V \rangle_S$$

inside the vector meson V

over the system or a sub-system S

STAR data indicate：

$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$$

means correlation !

- **How to describe quark spin correlations?**
- **How correlations affect hadronic-level properties?**

⇒ **a systematic study**

2 Description of quark spin correlations in HIC

Only spin degree of freedom is considered

- For single particle: the complete set $\{\mathbb{I}, \hat{\sigma}_{1i}\}$

$$\hat{\rho}^{(1)} = \frac{1}{2}(\mathbb{I} + P_{1i}\hat{\sigma}_{1i}) \qquad P_{1i} = \langle \hat{\sigma}_{1i} \rangle = Tr[\hat{\rho}^{(1)}\hat{\sigma}_{1i}]$$

- Two particle system (12): the complete set $\{\mathbb{I}_1, \hat{\sigma}_{1i}\} \otimes \{\mathbb{I}_2, \hat{\sigma}_{2j}\}$

we are used to

$$\hat{\rho}^{(12)} = \frac{1}{2^2}\left[\mathbb{I}_1 \otimes \mathbb{I}_2 + P_{1i}\hat{\sigma}_{1i} \otimes \mathbb{I}_2 + P_{2j}\mathbb{I}_1 \otimes \hat{\sigma}_{2j} + t_{ij}^{(12)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j}\right]$$

P_{1i} : polarization of particle 1 $\qquad$ P_{2j} : polarization of particle 2

$t_{ij}^{(12)}$: **spin correlation** between the two particles

Shortage: $t_{ij}^{(12)} = P_{1i}P_{2j} \neq 0$ if $\hat{\rho}^{(12)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)}$

propose

$$\hat{\rho}^{(12)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)} + \frac{1}{2^2}c_{ij}^{(12)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \qquad t_{ij}^{(12)} = c_{ij}^{(12)} + P_{1i}P_{2j} \qquad c_{ij}^{(12)} = \langle \hat{\sigma}_{1i}\hat{\sigma}_{2j} \rangle - \langle \hat{\sigma}_{1i} \rangle \langle \hat{\sigma}_{2j} \rangle$$

2 Description of quark spin correlations in HIC

☐ Take other degrees of freedom into account

- For single particle: $\hat{\rho}^{(1)}(\alpha)=\frac{1}{2}[\mathbb{I}+P_{1i}(\alpha)\hat{\sigma}_{1i}]$ **α : any other degree of freedom**

- Two particle system A= (12): $\hat{\rho}^{(12)}(\alpha_1,\alpha_2)=\hat{\rho}^{(1)}(\alpha_1)\otimes\hat{\rho}^{(2)}(\alpha_2)+\frac{1}{2^2}c_{ij}^{(12)}(\alpha_1,\alpha_2)\hat{\sigma}_{1i}\otimes\hat{\sigma}_{2j}$

Suppose A= (12) is in the state $|\alpha_{12}\rangle$, the α_{12} -dependence spin density matrix

$$\bar{\hat{\rho}}^{(12)}(\alpha_{12})=\langle\alpha_{12}|\hat{\rho}^{(12)}|\alpha_{12}\rangle$$

average inside A

$$=\bar{\hat{\rho}}^{(1)}(\alpha_{12})\otimes\bar{\hat{\rho}}^{(2)}(\alpha_{12})+\frac{1}{2^2}\bar{c}_{ij}^{(12)}(\alpha_{12})\hat{\sigma}_{1i}\otimes\hat{\sigma}_{2j}$$

The polarization $\bar{P}_{1i}(\alpha_{12})=\langle P_{1i}(\alpha_1)\rangle$ equals to P_{1i} averaged inside A

However, **the correlation** $\bar{c}_{ij}^{(12)}(\alpha_{12})\neq\langle c_{ij}^{(12)}(\alpha_1,\alpha_2)\rangle$ not equal to $c_{ij}^{(12)}$ averaged inside A

$$\bar{c}_{ij}^{(12)}(\alpha_{12})=\langle c_{ij}^{(12)}(\alpha_1,\alpha_2)\rangle+\bar{c}_{ij}^{(12,0)}(\alpha_{12})$$

"effective correlation" = "genuine correlation" + "induced correlation"

the observed — dynamical process — due to average over α_i

$$\bar{c}_{ij}^{(12,0)}(\alpha_{12})=\langle P_{1i}(\alpha_1)P_{2j}(\alpha_2)\rangle-\langle P_{1i}(\alpha_1)\rangle\langle P_{2j}(\alpha_2)\rangle$$

3 Correlations in HIC using non-relativistic quark combination model

For $q_1 + \bar{q}_2 \to V$, in general $\hat{\rho}^V = \hat{\mathcal{M}} \hat{\rho}^{(q_1\bar{q}_2)} \hat{\mathcal{M}}^\dagger$ $\hat{\mathcal{M}}$: transition operator

If only spin degree of freedom

$$\rho^V_{mm'} = \langle jm | \hat{\mathcal{M}} \hat{\rho}^{(q_1\bar{q}_2)} \hat{\mathcal{M}}^\dagger | jm' \rangle$$

$$= \sum_{m_n, m'_n} \langle jm | \hat{\mathcal{M}} | m_1 m_2 \rangle \langle m_1 m_2 | \hat{\rho}^{(q_1\bar{q}_2)} | m'_1 m'_2 \rangle \langle m'_1 m'_2 | \hat{\mathcal{M}}^\dagger | jm' \rangle$$

$$= N_V \sum_{m_n; m_n'} \langle jm | m_1 m_2 \rangle \langle m_1 m_2 | \hat{\rho}^{(q_1\bar{q}_2)} | m'_1 m'_2 \rangle \langle m'_1 m'_2 | jm' \rangle$$

independent of $\hat{\mathcal{M}}$

since

transition matrix

$$\langle jm | \hat{\mathcal{M}} | m_1 m_2 \rangle = \sum_{j'm'} \langle jm | \hat{\mathcal{M}} | j'm' \rangle \langle j'm' | m_1 m_2 \rangle$$

$$= \langle jm | \hat{\mathcal{M}} | jm \rangle \langle jm | m_1 m_2 \rangle$$

constant indepent of m Clebsch-Gordan coefficients

space rotation invariance demands:

① angular momentum conservation

$$j = j', m = m'$$

② $\langle jm | \hat{\mathcal{M}} | jm \rangle = \langle j \| \hat{\mathcal{M}} \| j \rangle$

This is also true if α-dependence but the wave function is factorized, i.e. $|jm, \alpha_V\rangle = |jm\rangle |\alpha_V\rangle$

$$\rho^V_{mm'}(\alpha_V) = \langle jm, \alpha_V | \hat{\mathcal{M}} \hat{\rho}^{(q_1\bar{q}_2)} \hat{\mathcal{M}}^\dagger | jm', \alpha_V \rangle$$

3-1 Spin density matrix for vector mesons

Spin alignment

$$\Rightarrow \quad \rho_{00}^{V}(\alpha_V)=\frac{1}{\bar{C}_V}\left\{1+\bar{c}_{xx}^{(q_1\bar{q}_2)}+\bar{c}_{yy}^{(q_1\bar{q}_2)}-\bar{c}_{zz}^{(q_1\bar{q}_2)}+\bar{P}_{q_1x}\bar{P}_{\bar{q}_2x}+\bar{P}_{q_1y}\bar{P}_{\bar{q}_2y}-\bar{P}_{q_1z}\bar{P}_{\bar{q}_2z}\right\}$$

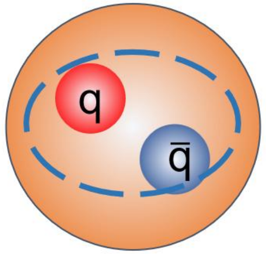
The vector meson's off-diagonal element

$$\bar{C}_V=\mathrm{Tr}\,\hat{\rho}^V=3+\bar{c}_{ii}^{(q_1\bar{q}_2)}+\bar{P}_{q_1i}\bar{P}_{\bar{q}_2i}$$

$$\rho_{10}^{V}(\alpha_V)=\frac{1}{\sqrt{2}\,\bar{C}_V}\Big\{\bar{c}_{xz}^{(q_1\bar{q}_2)}+\bar{c}_{zx}^{(q_1\bar{q}_2)}+\bar{P}_{q_1x}\big(1+\bar{P}_{\bar{q}_2z}\big)+\big(1+\bar{P}_{q_1z}\big)\bar{P}_{\bar{q}_2x}$$
$$-i\Big[\bar{c}_{yz}^{(q_1\bar{q}_2)}+\bar{c}_{zy}^{(q_1\bar{q}_2)}+\bar{P}_{q_1y}\big(1+\bar{P}_{\bar{q}_2z}\big)+\big(1+\bar{P}_{q_1z}\big)\bar{P}_{\bar{q}_2y}\Big]\Big\},$$

$$\rho_{0-1}^{V}(\alpha_V)=\frac{1}{\sqrt{2}\,\bar{C}_V}\Big\{-\bar{c}_{xz}^{(q_1\bar{q}_2)}-\bar{c}_{zx}^{(q_1\bar{q}_2)}+\bar{P}_{q_1x}\big(1-\bar{P}_{\bar{q}_2z}\big)+\big(1-\bar{P}_{q_1z}\big)\bar{P}_{\bar{q}_2x}$$
$$+i\Big[\bar{c}_{yz}^{(q_1\bar{q}_2)}+\bar{c}_{zy}^{(q_1\bar{q}_2)}-\bar{P}_{q_1y}\big(1-\bar{P}_{\bar{q}_2z}\big)-\bar{P}_{\bar{q}_2y}\big(1-\bar{P}_{q_1z}\big)\Big]\Big\},$$

$$\rho_{1-1}^{V}(\alpha_V)=\frac{1}{\bar{C}_V}\Big\{\bar{c}_{xx}^{(q_1\bar{q}_2)}-\bar{c}_{yy}^{(q_1\bar{q}_2)}+\bar{P}_{q_1x}\bar{P}_{\bar{q}_2x}-\bar{P}_{q_1y}\bar{P}_{\bar{q}_2y}-i\Big[\bar{c}_{xy}^{(q_1\bar{q}_2)}+\bar{c}_{yx}^{(q_1\bar{q}_2)}+\bar{P}_{q_1x}\bar{P}_{\bar{q}_2y}+\bar{P}_{q_1y}\bar{P}_{\bar{q}_2x}\Big]\Big\},$$



Only local spin correlations !

Sensitive to the local spin correlation between q_1 and $\bar{q}_2$.

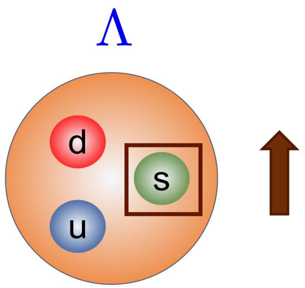
3-2 Global hyperon polarization

Λ polarization

$$\boldsymbol{q}_1+\boldsymbol{q}_2+\boldsymbol{q}_3\rightarrow \boldsymbol{H}$$

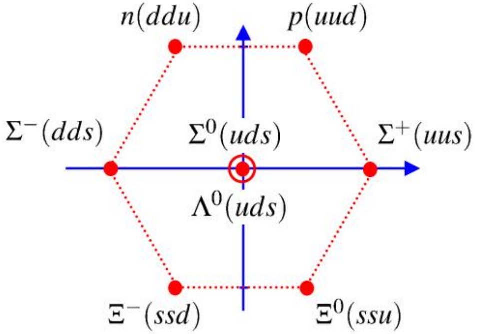
$$P_{\Lambda n}(\alpha_\Lambda)=\bar{P}_{sn}-\frac{\bar{c}_{iin}^{(uds)}+\bar{c}_{in}^{(us)}\bar{P}_{di}+\bar{c}_{in}^{(ds)}\bar{P}_{ui}}{1-\bar{c}_{ii}^{(ud)}-\bar{P}_{ui}\bar{P}_{di}}, \qquad n=x,y,z$$

contribution from quark spin correlations



For other $J^P=(1/2)^+$ hyperons

$$P_{H_{112}n}=\frac{1}{3}(4P_{q_1n}-P_{q_2n})+\frac{\delta\rho_{H_{112}}}{C_{H_{112}}} \qquad P_{\Sigma^0 n}=\frac{1}{3}(2P_{un}+2P_{dn}-P_{sn})+\frac{\delta\rho_{\Sigma^0}}{C_{\Sigma^0}}$$



$\delta\rho_{H_{112}}, C_{H_{112}}, \delta\rho_{\Sigma_0}, C_{\Sigma_0}$ are given in **Phys. Rev. D 109, 114003 (2024)**

By studying P_H, study the average of quark polarization $\bar{P}_q$.

3-3 Global hyperon-(anti)hyperon spin correlation

For spin-1/2 hyperon pair $H_1\bar{H}_2$ or $H_1 H_2$, the spin correlations

$$c_{nn}^{H_1\bar{H}_2} = \frac{f_{++}^{H_1\bar{H}_2} + f_{--}^{H_1\bar{H}_2} - f_{+-}^{H_1\bar{H}_2} - f_{-+}^{H_1\bar{H}_2}}{f_{++}^{H_1\bar{H}_2} + f_{--}^{H_1\bar{H}_2} + f_{+-}^{H_1\bar{H}_2} + f_{-+}^{H_1\bar{H}_2}}$$

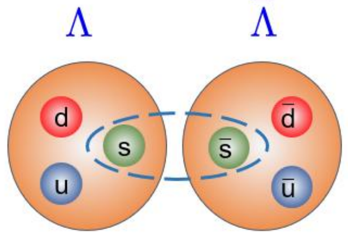
quark spin correlation: $\boldsymbol{q_1 + q_2 + q_3 \to H_1}$ $\boldsymbol{\bar{q}_4 + \bar{q}_5 + \bar{q}_6 \to \bar{H}_2}$

qq: $$\bar{c}_{ij}^{(q_1 q_2)}(\alpha_{H_1}, \alpha_{\bar{H}_2}) = \sum_{\alpha_n} \left[c_{ij}^{(q_1 q_2)}(\alpha_{q_1}, \alpha_{q_2}) + P_{q_1 i}(\alpha_{q_1}) P_{q_2 j}(\alpha_{q_2}) \right] \left| \langle \alpha_n | \alpha_{H_1} \rangle \right|^2 - \bar{P}_{q_1 i}(\alpha_{H_1}) \bar{P}_{q_2 j}(\alpha_{H_1})$$

$q\bar{q}$: $$\bar{c}_{ij}^{(q_1 \bar{q}_2)}(\alpha_{H_1}, \alpha_{\bar{H}_2}) = \sum_{\alpha_n, \alpha_m} c_{ij}^{(q_1 \bar{q}_2)}(\alpha_{q_1}, \alpha_{\bar{q}_2}) \left| \langle \alpha_n | \alpha_{H_1} \rangle \right|^2 \left| \langle \alpha_m | \alpha_{\bar{H}_2} \rangle \right|^2$$

only long range, no induced contributions

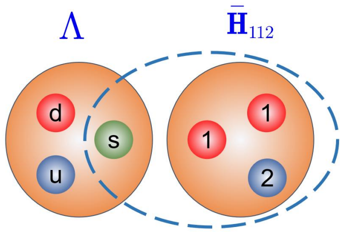
$$c_{zz}^{\Lambda\bar{\Lambda}}(\alpha_\Lambda, \alpha_{\bar{\Lambda}}) \approx P_{\Lambda z}(\alpha_\Lambda) P_{\bar{\Lambda} z}(\alpha_{\bar{\Lambda}}) + \bar{c}_{zz}^{(s\bar{s})} - \frac{\bar{P}_{sz}}{\bar{C}_\Lambda}\left[\bar{c}_{iz}^{(d\bar{s})} \bar{P}_{ui} + \bar{c}_{iz}^{(u\bar{s})} \bar{P}_{di}\right] - \frac{\bar{P}_{\bar{s}z}}{\bar{C}_{\bar{\Lambda}}}\left[\bar{c}_{zi}^{(s\bar{d})} \bar{P}_{\bar{u}i} + \bar{c}_{zi}^{(s\bar{u})} \bar{P}_{\bar{d}i}\right]$$



Sensitive to the long range spin correlation between s and $\bar{s}$.

3-3 Global hyperon-(anti)hyperon spin correlation

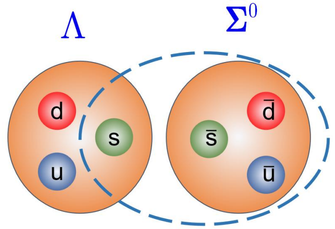
- Λ and $\bar{H}_{112}$



$$c_{zz}^{\Lambda\bar{H}_{112}}(\alpha_\Lambda\alpha_{\bar{H}_{112}})\approx P_{\Lambda z}(\alpha_\Lambda)P_{\bar{H}_{112}z}(\alpha_{\bar{H}_{112}})+\frac{\mathcal{B}_f^{(s)}}{3}-\frac{\bar{P}_q^2}{3\bar{C}'_\Lambda}\left[\mathcal{B}_f^{(u)}+\mathcal{B}_f^{(d)}\right]-\frac{2\bar{P}_{\bar{q}}^2}{\bar{C}'_{\bar{H}_{112}}}\left[2\bar{c}_{zz}^{(s\bar{q}_2)}+\bar{c}_{zz}^{(s\bar{q}_1)}\right]$$

- Λ and $\bar{\Sigma}^0$

$$\mathcal{A}_f^{(q)}=2\left(c_{zz}^{(q\bar{u})}+c_{zz}^{(q\bar{d})}\right)-c_{zz}^{(q\bar{s})} \qquad \mathcal{B}_f^{(q)}=4\bar{c}_{zz}^{(q\bar{q}_1)}-\bar{c}_{zz}^{(q\bar{q}_2)}$$



$$c_{zz}^{\Lambda\bar{\Sigma}^0}(\alpha_\Lambda\alpha_{\bar{\Sigma}^0})\approx P_{\Lambda z}(\alpha_\Lambda)P_{\bar{\Sigma}^0 z}(\alpha_{\bar{\Sigma}^0})+\frac{\mathcal{A}_f^{(s)}}{3}-\frac{\bar{P}_q^2}{3\bar{C}'_\Lambda}\left[\mathcal{A}_f^{(u)}+\mathcal{A}_f^{(d)}\right]-\frac{P_{\bar{q}}^2}{\bar{C}'_{\bar{\Sigma}^0}}\left[4\bar{c}_{zz}^{(s\bar{s})}+\bar{c}_{zz}^{(s\bar{u})}+\bar{c}_{zz}^{(s\bar{d})}\right]$$

no flavor-depdence

$$c_{zz}^{H_1\bar{H}_2}(\alpha_{H_1},\alpha_{\bar{H}_2})\approx P_{H_1}(\alpha_{H_1})P_{\bar{H}_2}(\alpha_{\bar{H}_2})+\bar{c}_{zz}^{(q\bar{q})}$$

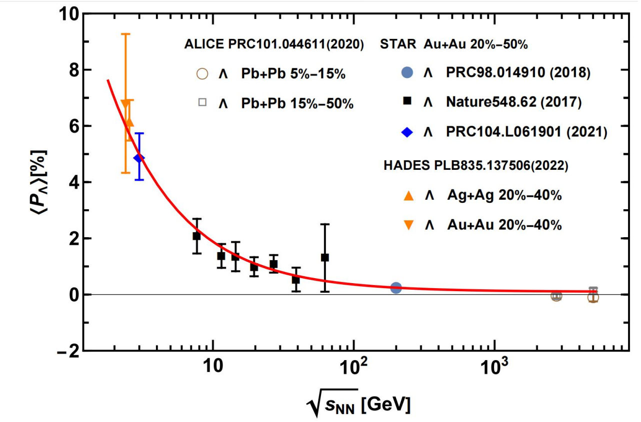
For the complete results, seen in:

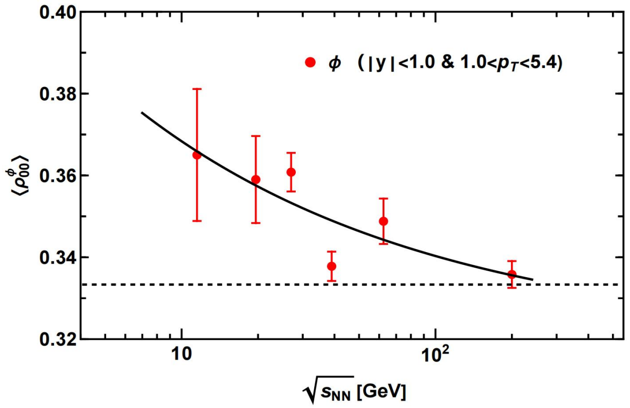
Ji-peng Lv, Zi-han Yu, Zuo-tang Liang, paper in preparation (2025)

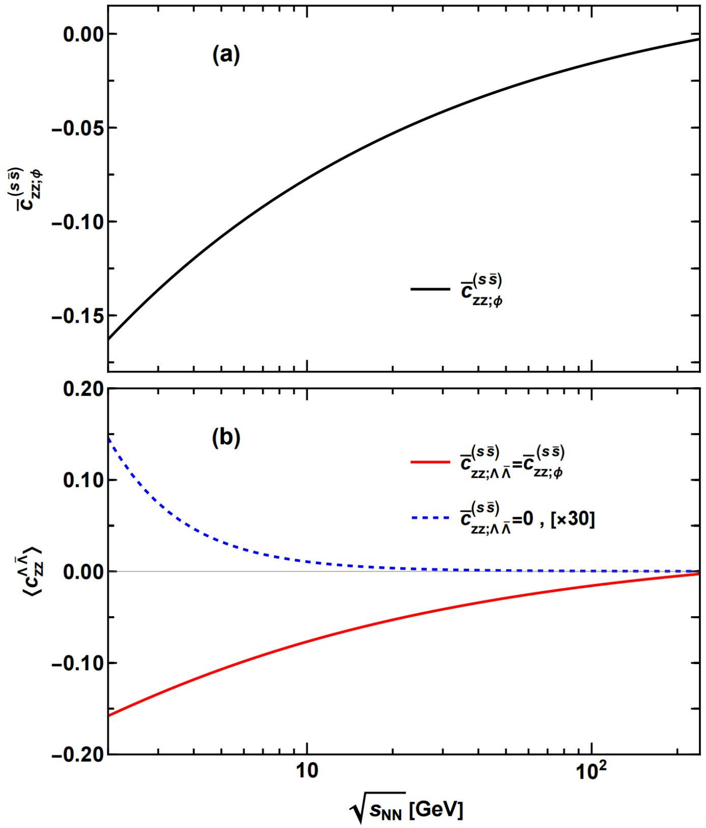
3-4 Numerical estimates

In principle, we can extract quark polarizations P_q and spin correlations $c_{ij}^{(q_1\bar{q}_2)}$ from available data, and make predication for other measurements.

A very rough estimation is made by keeping only leading terms,







$$(1)\ \langle P_\Lambda \rangle \sim \langle P_s \rangle$$

$$(2)\ \langle \rho_{00}^{\phi} \rangle \sim \frac{1-\bar{c}_{zz;\phi}^{(s\bar{s})}-\langle P_s \rangle^2}{3+\bar{c}_{zz;\phi}^{(s\bar{s})}+\langle P_s \rangle^2}$$

$$(3)\ \langle c_{zz}^{\Lambda\bar{\Lambda}} \rangle \sim \bar{c}_{zz;\Lambda\bar{\Lambda}}^{(s\bar{s})}+\langle P_s \rangle^2$$

- Case 1: no quark spin correlation
- Case 2: $\bar{c}_{zz;\phi}^{(s\bar{s})} = \bar{c}_{zz;\Lambda\bar{\Lambda}}^{(s\bar{s})}$

local **long range**

4 Summary and outlook

- Hyperon global polarization reflects the average quark polarization, vector meson spin alignment is sensitive to quark-antiquark spin correlations, **opening a window to study quark spin correlations in HIC**.

- Quark spin correlations are classified into local and long range. **Effective correlations** contain **genuine correlations** from dynamics and **induced correlations** due to average over other degrees of freedom.

- **Vector meson density matrix elements** may provide important information on the **local** correlations, while **hyperon-(anti)hyperon spin correlation** are sensitive to **long range** quark spin correlations.

- For spin-3/2 baryons, see **9-24 Zi-han Yu's talk.**

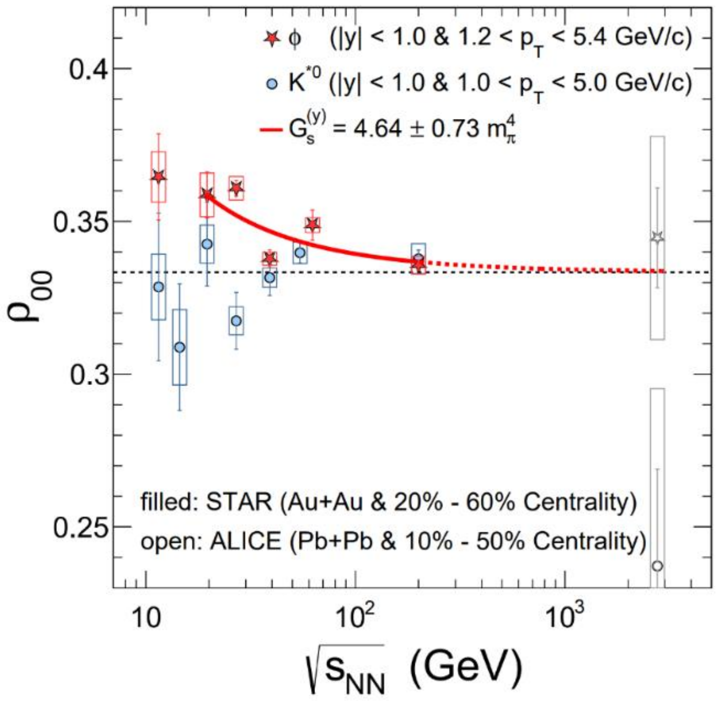
Thank you !

Back up

Local correlation or long range correlation

The STAR data show that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

Zuo-Tang Liang, SPIN 2023

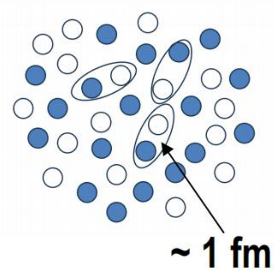


STAR, **Nature 614, 244 (2023).**

$$\langle P_q P_{\bar{q}} \rangle = \langle \langle P_q P_{\bar{q}} \rangle_V \rangle_S$$

inside the vector meson V

over the whole system or a sub-system S



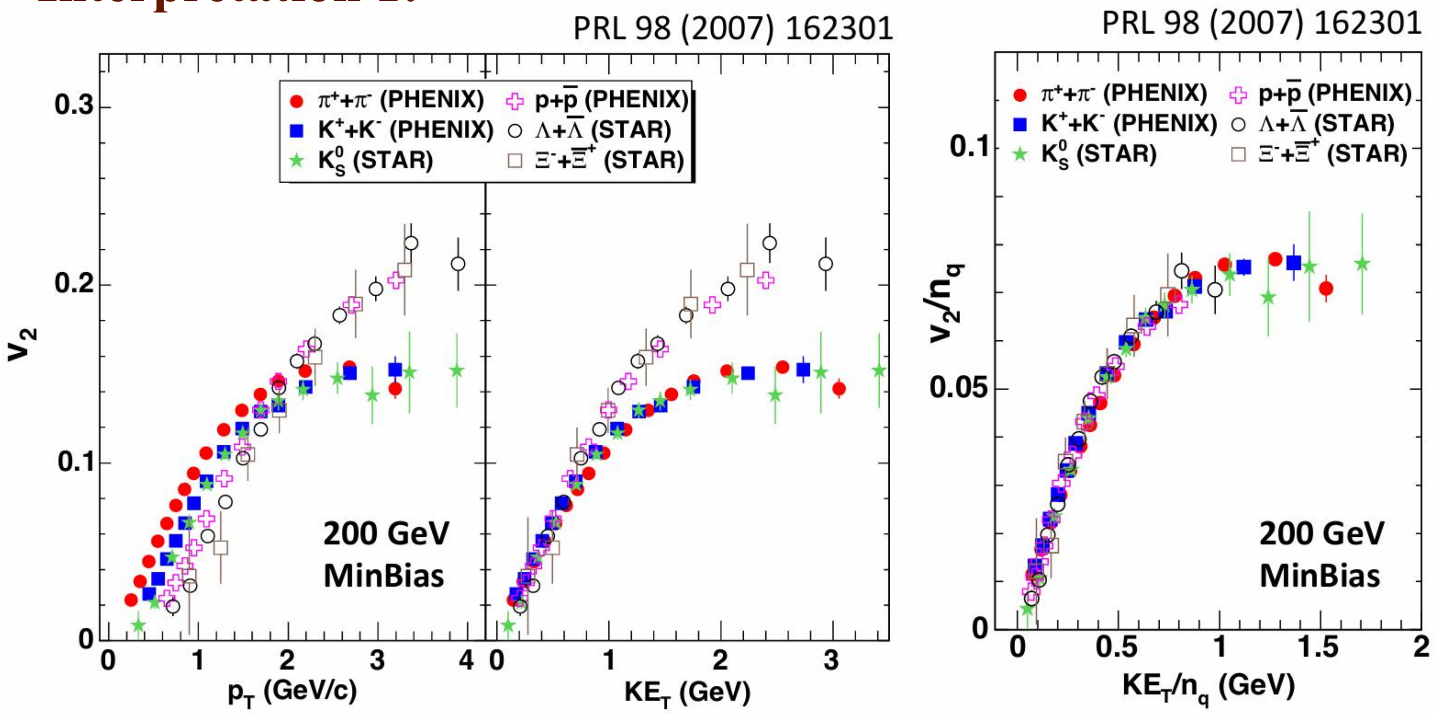
(1) **local correlation:** $\langle P_q P_{\bar{q}} \rangle_V \neq \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V$

(2) **long range correlation:** $\langle P_q P_{\bar{q}} \rangle_V = \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V$

$$\langle \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V \rangle_S \neq \langle \langle P_q \rangle_V \rangle_S \langle \langle P_{\bar{q}} \rangle_V \rangle_S$$

Why quark combination model

Interpretation 1:



$$q+\bar{q}\to V \qquad q_1+q_2+q_3\to B$$

$$p_{\perp 1}=p_{\perp 2}=\frac{p_T}{2} \qquad p_{\perp 1}=p_{\perp 2}=p_{\perp 3}=\frac{p_T}{3}$$

$$f_M(p_T,\varphi)=f_q^2\left(\frac{p_T}{2},\varphi\right)$$

$$f_B(p_T,\varphi)=f_q^3\left(\frac{p_T}{3},\varphi\right)$$

- Meson/Baryon splitting: Quark combination
- Number of Constituent Quark scaling: Parton degree of freedom

Interpretation 2:

$$|P\rangle=f_0|qqq\rangle+f_1\,|qqqg\rangle+f_2\,|qqq\bar{q}q\rangle+\cdots \qquad \text{Fock state}$$

Measurement and sensitive quark spin quantities

Hadron	Measurables	sensitive quantities
spin-1/2 (hyperon H)	Hyperon polarization P_H	**average** quark polarization $\langle P_q \rangle$
	Hyperon spin correlation $c_{H_1H_2}, c_{H_1\bar{H}_2}$	**long range** spin correlations $c_{qq}, c_{q\bar{q}}$
spin-1 (Vector mesons)	Spin alignment ρ_{00}	**local** spin correlations $c_{q\bar{q}}$
	off-diagnal elements $\rho_{m'm}$	**local** spin correlations $c_{q\bar{q}}$
spin-3/2 $J^P = \left(\frac{3}{2}\right)^+$ baryons	Hyperon polarization S_L	**average** quark polarization $\langle P_q \rangle$
	Rank 2 tensor polarization S_{LL}	**local** spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	**local** spin correlations c_{qqq}

Systematic studies of quark spin correlations in QGP!

Global hyperon-(anti)hyperon spin correlation

$$\hat{\rho}^{(1\cdots6)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)} \otimes \hat{\rho}^{(3)} \otimes \hat{\rho}^{(4)} \otimes \hat{\rho}^{(5)} \otimes \hat{\rho}^{(6)}$$

$$+ \frac{1}{2^2}\left[c_{ij}^{(12)} \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\rho}^{(3)} \otimes \hat{\rho}^{(4)} \otimes \hat{\rho}^{(5)} \otimes \hat{\rho}^{(6)} + 14 \text{ exchange terms } \right]$$

$$+ \frac{1}{2^3}\left[c_{ijk}^{(123)} \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\sigma}_{3k} \otimes \hat{\rho}^{(4)} \otimes \hat{\rho}^{(5)} \otimes \hat{\rho}^{(6)} + 19 \text{ exchange terms } \right]$$

$$+ \frac{1}{2^4}\left[c_{ijkl}^{(1234)} \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\sigma}_{3k} \otimes \hat{\sigma}_{4l} \otimes \hat{\rho}^{(5)} \otimes \hat{\rho}^{(6)} + 14 \text{ exchange terms } \right]$$

$$+ \frac{1}{2^5}\left[c_{ijklm}^{(12345)} \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\sigma}_{3k} \otimes \hat{\sigma}_{4l} \otimes \hat{\sigma}_{5m} \otimes \hat{\rho}^{(6)} + 5 \text{ exchange terms } \right]$$

$$+ \frac{1}{2^6} c_{ijklmn}^{(123456)} \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\sigma}_{3k} \otimes \hat{\sigma}_{4l} \otimes \hat{\sigma}_{5m} \otimes \hat{\sigma}_{6n}$$

The spin correlation of $\Lambda\bar{\Lambda}$

$$c_{zz}^{\Lambda\bar{\Lambda}} = P_{sz} P_{\bar{s}z} + \frac{1}{C_{\Lambda\bar{\Lambda}}} \Big\{ c_{zz}^{(s\bar{s})} (1 - P_{ui} P_{di}) \left(1 - P_{\bar{u}i} P_{\bar{d}i}\right)$$

$$- P_{sz} \Big[\left(c_{iz}^{(d\bar{s})} P_{ui} + c_{iz}^{(u\bar{s})} P_{di}\right) \left(1 - P_{\bar{u}i} P_{\bar{d}i}\right) + \left(c_{iz}^{(\bar{d}\bar{s})} P_{\bar{u}i} + c_{iz}^{(\bar{u}\bar{s})} P_{\bar{d}i}\right) (1 - P_{ui} P_{di}) \Big]$$

$$- P_{\bar{s}z} \Big[\left(c_{iz}^{(ds)} P_{ui} + c_{iz}^{(us)} P_{di}\right) \left(1 - P_{\bar{u}i} P_{\bar{d}i}\right) + \left(c_{iz}^{(\bar{d}s)} P_{\bar{u}i} + c_{iz}^{(\bar{u}s)} P_{\bar{d}i}\right) (1 - P_{ui} P_{di}) \Big] \Big\}$$

Global hyperon-(anti)hyperon spin correlation

- H_{112} and $\bar{H}_{112}$

$$c_{zz}^{H_{112}\bar{H}_{112}}(\alpha_{H_{112}},\alpha_{\bar{H}_{112}}) \approx P_{H_{112}z}(\alpha_{H_{112}})P_{\bar{H}_{112}z}(\alpha_{\bar{H}_{112}}) + \frac{4\mathcal{B}_f^{(\bar{q}_1)} - \mathcal{B}_f^{(\bar{q}_2)}}{9} - \frac{2\bar{P}_q^2}{3\bar{C}'_{H_{112}}}\left[2\mathcal{B}_{\bar{f}}^{(q_2)} + \mathcal{B}_{\bar{f}}^{(q_1)}\right] - \frac{2\bar{P}_{\bar{q}}^2}{3\bar{C}'_{\bar{H}_{112}}}\left[2\mathcal{B}_f^{(\bar{q}_2)} + \mathcal{B}_f^{(\bar{q}_1)}\right]$$

- H_{112} and $\bar{\Sigma}^0$

$$c_{zz}^{H_{112}\bar{\Sigma}^0}(\alpha_{H_{112}},\alpha_{\bar{\Sigma}^0}) \approx P_{H_{112}z}(\alpha_{H_{112}})P_{\bar{\Sigma}^0 z}(\alpha_{\bar{\Sigma}^0}) + \frac{4\mathcal{A}_{\bar{f}}^{(q_1)} - \mathcal{A}_{\bar{f}}^{(q_2)}}{9} - \frac{2\bar{P}_q^2}{3\bar{C}'_{H_{112}}}\left[2\mathcal{A}_{\bar{f}}^{(q_2)} + \mathcal{A}_{\bar{f}}^{(q_1)}\right] - \frac{\bar{P}_{\bar{q}}^2}{3\bar{C}'_{\bar{\Sigma}^0}}\left[4\mathcal{B}_f^{(\bar{s})} + \mathcal{B}_f^{(\bar{u})} + \mathcal{B}_f^{(\bar{d})}\right]$$

- Σ^0 and $\bar{\Sigma}^0$

$$c_{zz}^{\Sigma^0\bar{\Sigma}^0}(\alpha_{\Sigma^0},\alpha_{\bar{\Sigma}^0}) \approx P_{\Sigma^0 z}(\alpha_{\Sigma^0})P_{\bar{\Sigma}^0 z}(\alpha_{\bar{\Sigma}^0}) + \frac{2\mathcal{A}_f^{(\bar{u})} + 2\mathcal{A}_f^{(\bar{d})} - \mathcal{A}_f^{(\bar{s})}}{9} - \frac{\bar{P}_q^2}{3\bar{C}'_{\Sigma^0}}\left[4\mathcal{A}_{\bar{f}}^{(s)} + \mathcal{A}_{\bar{f}}^{(d)} + \mathcal{A}_{\bar{f}}^{(u)}\right] - \frac{\bar{P}_{\bar{q}}^2}{3\bar{C}'_{\bar{\Sigma}^0}}\left[4\mathcal{A}_f^{(\bar{s})} + \mathcal{A}_f^{(\bar{d})} + \mathcal{A}_f^{(\bar{u})}\right]$$

$$\mathcal{A}_f^{(\bar{q})} = 2\left(c_{zz}^{(u\bar{q})} + c_{zz}^{(d\bar{q})}\right) - c_{zz}^{(s\bar{q})} \qquad \mathcal{A}_{\bar{f}}^{(q)} = 2\left(c_{zz}^{(q\bar{u})} + c_{zz}^{(q\bar{d})}\right) - c_{zz}^{(q\bar{s})}$$

$$\mathcal{B}_f^{(\bar{q})} = 4\bar{c}_{zz}^{(q_1\bar{q})} - \bar{c}_{zz}^{(q_2\bar{q})} \qquad \mathcal{B}_{\bar{f}}^{(q)} = 4\bar{c}_{zz}^{(q\bar{q}_1)} - \bar{c}_{zz}^{(q\bar{q}_2)}$$

Ji-peng Lv, Zi-han Yu, Zuo-tang Liang, paper in preparation (2025)

Sensitive to the long range spin correlation between q_1 and $\bar{q}_2$.

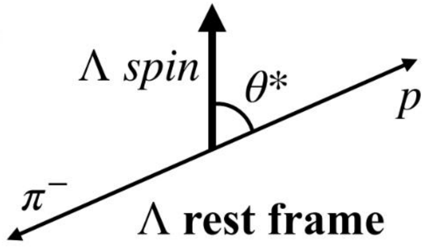
Experimental Measurements

In non-central AA collision:

Global polarization of quarks & anti-quarks → **hadronization** → **Global polarization of hadrons**

- **Global hyperon polarization** eg: $\Lambda \rightarrow p + \pi$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_\Lambda P_\Lambda \cos\theta^*)$$

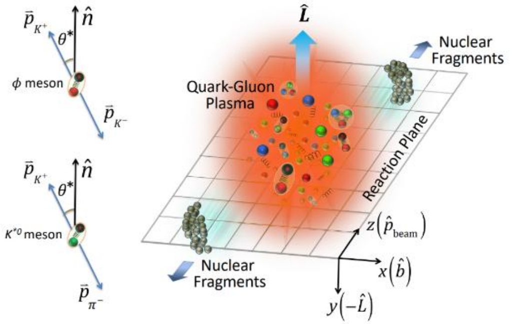


- **Global vector meson spin alignment** $V \rightarrow M_1 + M_2$

$\phi(s\bar{s}), K^{*0}(d\bar{s})$

mainly decay: $K^{*0} \rightarrow K^+ + \pi^-$ $\phi \rightarrow K^+ + K^-$

$$\frac{dN}{d\cos\theta^*} = \int_0^{2\pi} d\phi \frac{dN}{d\Omega} = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$



Polar angle distribution depends only on ρ_{00} !

STAR, **Nature 614, 244 (2023).**